LCA Methodology

Product Specific Emissions from Municipal Solid Waste Landfills

Part II: Presentation and Verification of the Computer Tool LCA-LAND
Part I: Landfill Modell (Int. J. LCA 3 (3) 158-168, 1998)

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Abstract

This paper presents and verifies the computer tool LCA-LAND for estimation of emissions from specific waste products disposed in municipal solid waste landfills in European countries for use in the inventory analysis of LCA. Examples of input data (e.g. distribution of the waste product in different countries, composition of the product and physical/chemical/biological properties of waste product components) and output data (e.g. estimated emissions to atmosphere and water) are given for a fictive waste product made of representative types of components (toluene, cellulose, polyvinylchloride (PVC), copper and chloride). Since waste products from different processes in the product system may be disposed at different landfills where they are mixed with waste originating outside the product system, the estimated emissions from specific waste products cannot be compared with measured emissions from true landfills. Hence, the computer tool is verified in terms of mass balances and sensitivity analyses. The mass balances agree exactly and the sensitivity analyses show that different types of waste product components behave differently in different types of landfills. Emission of e.g. toluene is significantly reduced in the presence of landfill top-cover, landfill gas combustion units and leachate treatment units. Generally, the sensitivity analysis shows good agreement between the relative proportions of various types of emissions (based on properties of the waste and properties of landfills) and good agreement with emission levels that would be expected based on a general understanding of landfill processes.

Keywords: Computer tool, LCA-LAND, landfills; gas combustion, landfills; inorganic non-metals, emissions, landfills; landfill model, municipal solid waste, product specific emissions; landfills, product specific emissions; LCA-LAND, computer tool, landfills; leachate treatment, landfills; metals, emissions, landfills; organic compounds, emissions, landfills; polymers, emissions, landfills; waste products, emission, landfills

Part II: Presentation and Verification of the Computer Tool LCA-LAND

1 Introduction

Life Cycle Assessment (LCA) is an environmental management tool used to examine and evaluate the environmental impacts associated with the existence of products. The focus of LCA is on the entire life cycle of the product, i.e. from the extraction of the raw materials through the production of materials and components and the manufacture, transportation and use of the product to the final disposal and possible recycling of the product (Consoli et al., 1993).

Although LCA has developed significantly during recent years, product specific emissions from disposed waste have only got minor attention in the literature (Finnveden et al., 1995; Finnveden, 1996) leaving a significant gap in the inventory phase of the LCA. At present, no systematic methods exist for determination of emissions from products after disposal meaning that emissions from waste treatment processes are often disregarded. Instead, the output from waste treatment processes in the LCA inventory analysis is frequently given as a quantity of solid waste and possibly some recovered energy from waste incineration (Wenzel et al., 1997).

In addition to the final disposal of the product, waste may arise from all life cycle stages of the product (extraction stage, production stage and use stage). Thus, the existence of a product will result in waste in a variety of different countries determined by the composition of the product, the international organization of suppliers behind the product and the international distribution through sale of the product.

The purpose of this paper is to present a computer tool, LCA-LAND for estimation of emissions from waste products disposed at municipal solid waste landfills in European countries exemplified by The Netherlands, Germany and Denmark. The computer tool is based on a large number of assumptions and approximations concerning, e.g. landfill construction and landfill conditions which are reported and discussed by NIELSEN and HAUSCHILD (1998). At the present stage, the computer tool should be considered as a framework for estimation of emissions from disposed waste products at prototype level. In the future, the tool should be extended to cover more countries and a large database of the most important waste products and components should be added. The prototype of LCA-LAND contains a built-in manual and is available for free download at http://www.ipt.dtu.dk/employ/pn.htm.

2 Method

2.1 System definitions and nomenclature

The system definitions and nomenclature are described in detail by NIELSEN and HAUSCHILD (1998) and only a brief summary of the most important aspects are provided in Table 1.

2.2 Concept of LCA-LAND

In order to estimate emissions from a waste product disposed in landfills in various countries with different types of landfill technology the product is divided into a number of subunits as illustrated in **Figure 1.** The total volume of the box represents the total weight of the product, the volumes of component-compartments represent the amount of each component, the volumes of country-compartments represent the amount of the waste product disposed in each country, the volumes of landfill type compartments (L1 to L4) represent the amount of the waste product disposed at various landfill types, and the volumes of landfill gas combustion compartments represent the amount of the waste product disposed at landfills equipped with landfill gas combustion facilities.

Table 1: System definitions and nomenclature

Object of the study:	Any kind of waste products disposed at landfills. "Waste product" is the term used for substances disposed at landfills. "Component" is the term used for parts of the waste products which are treated individually in estimation of emissions
Types of landfills:	Municipal solid waste landfills only
Geographic area:	European countries with average precipitation
External pollution Control systems:	Leachate collection and treatment, landfill gas collection and combustion
Time perspective for estimated emissions:	100 years
Physical borders:	Bottom of landfill (between original geological material and waste/bottom barrier). Top of landfill (between atmosphere and top of waste/top-cover)

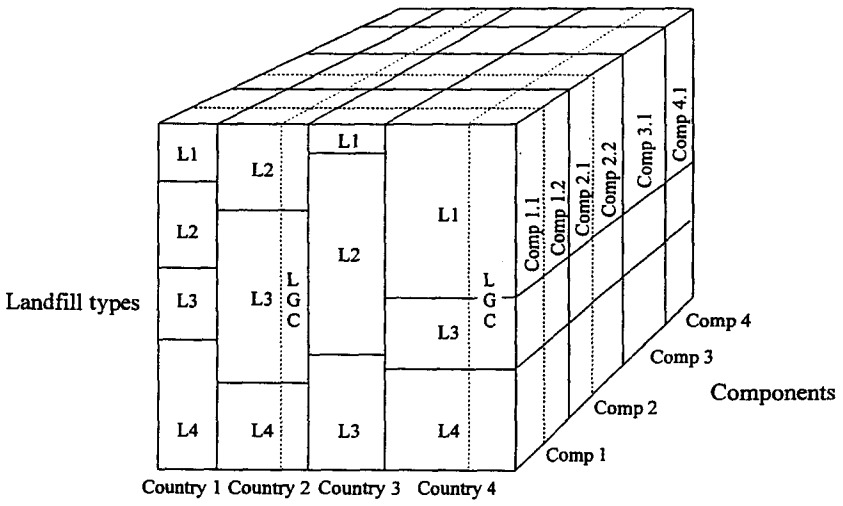

Fig. 1: Schematic representation of the division of a waste product into components (Comp1.1 to Comp4.1), recipient countries (Country 1 to 4) and landfill types (L1 to L4). The total volume of the box represent the total mass of the waste product and volumes of compartments represent fractions of the waste product on a weight basis. LGC-compartments represent the amount of waste product disposed at landfills equipped with landfill gas combustion facilities

The information about the geographic distribution of the waste product is used to determine the amount disposed at each landfill type. It is assumed that identical landfill types in different countries are similar with respect to emissions (→ *section 2.4*) and the information about the geographic distribution is not used any further. In the modeling, landfill gas combustion (LGC) is assumed to be independent of the landfill type (L1 to L4), explaining the crossing of LGC and landfill types.

Emissions from different components in different landfill types are determined individually and summed up for the inventory of the entire product. The estimation of emissions from component 1.1 disposed in landfill type L1 is illustrated as an example in **Figure 2**. The total mass of component 1.1 disposed in countries 1, 3 and 4 enters a specific model (L1-Comp1) in which the emissions and remains from the disposed product are calculated.

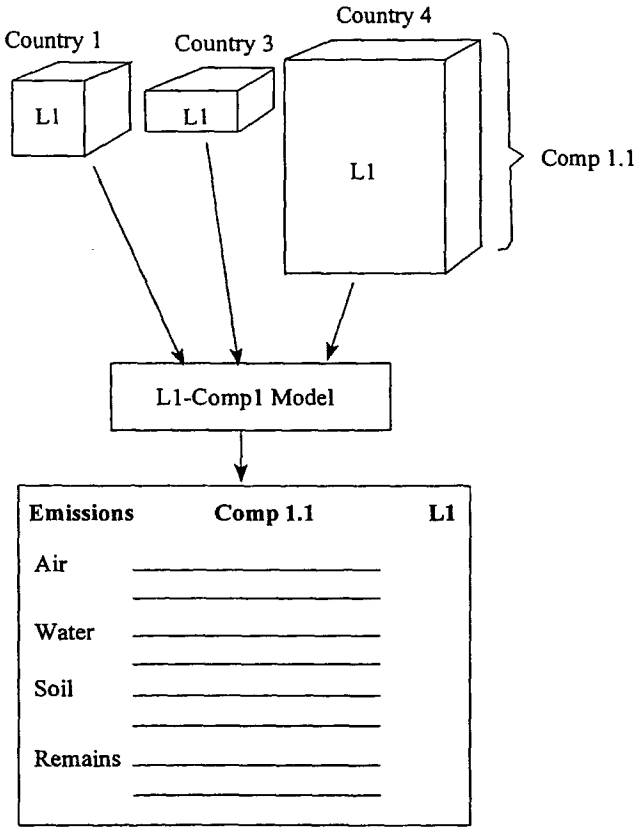

Fig. 2: Schematic representation of the estimation of emissions from Comp1.1 in landfill type L1. The result of the modeling is a table of emissions to air, water and soil during 100 years plus remains in the landfill after 100 years. The total volume of the three L1-Comp1.1 boxes represent the total mass of Comp1.1 treated in landfill type L1

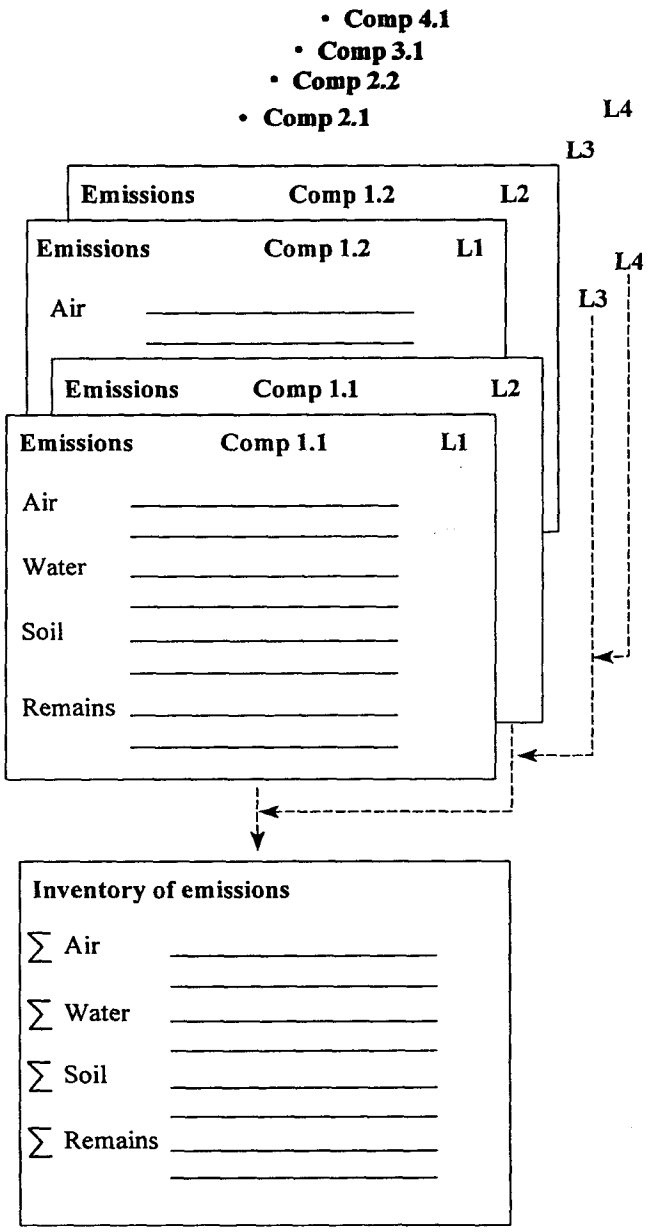

Fig. 3: Schematic representation of the aggregation of the total emissions from the entire waste product treated as waste in landfill types L1 to L4

The aggregation of emissions to the environment from all waste product components at each landfill type is illustrated in **Figure 3**. The tool presented in this paper automatically summarizes emissions from each component, while aggregation of emissions from different components must so far be done manually.

The landfill types and component groups used in LCA-LAND as well as modeling assumptions and approximations are described and discussed by NIELSEN and HAUSCHILD (1998).

2.3 Description of LCA-LAND

The LCA-LAND computer tool is constructed in Excel® and is build up of 17 interrelated sheets. A brief description of the function of each sheet is given in **Table 2.** Sheets 1 to 6 are prepared for data input (product and component characteristics as well as landfill profiles). Sheets 7 and 8 simulate the distribution coefficients for specific organic compounds (SOCs) (NIELSEN and HAUSCHILD, 1998; KJELDSEN and CHRISTENSEN, 1997). Sheets 9 to 11 calculate the mass distribution of the waste (e.g. between different landfill types). Sheets 12 to 14 calculate emissions to the atmosphere, water and soil from various types of landfills (directly or via leachate treatment plants or landfill gas combustion plants) and remains in the landfill. Sheets 15 to 17 summarize and present the inventory.

Table 2: Brief description of the function of spreadsheets

Sheet #	Name	Function	Parameter
1	Component	Data input	Component name and weight
2	International	Data input	Distribution of the waste product between countries
3	Landfill profiles	Data input	National landfill profiles. Default profiles available for DK, NL, D in 1995
4	Stoichiometry	Data input	Stoichiometric conversion factors (e.g. g CO_2 produced pr. g degraded cellulose)
5	Metal	Data input	Distribution coefficients for individual metals
6	Organic	Data input	Physical, chemical and biological constants for individual SOCs [a]
7	SOC[a] (cover)	Simulation	Distribution coefficients for SOCs at landfills equipped with synthetic cover or clay cover
8	SOC[a] (no cover)	Simulation	Distribution coefficients for SOCs at landfills without top-cover or equipped with soil top-cover
9	Distribution (1)	Calculation	Mass distribution of components between landfill types L1 to L4
10	Distribution (2)	Calculation	Fractions of substances emitted with landfill gas and leachate, prior to leachate and landfill gas collection
11	Distribution (3)	Calculation	Fractions of substances emitted to atmosphere and aquatic recipients after leachate and landfill gas collection and treatment
12	Landfill	Calculation	Emissions to the environment directly from landfills
13	LT	Calculation	Emissions to the environment from landfills via leachate treatment (LT) plants
14	LGC	Calculation	Emissions and energy production from the landfills via landfill gas combustion (LGC) plants
15	Sum	Calculation	Summarized emissions from landfills (directly) and via LT- and LGC plants
16	Total	Calculation	Preparation of data for the inventory
17	Inventory	Data output	Presentation of the inventory. Emissions to atmosphere, water and soil during 100 years plus remains in the landfill after 100 years

[a] SOC: specific organic compounds

2.4 National landfill profiles

As already noted, the quantity and composition of emissions from disposed waste products are determined by the actual conditions in the landfill and the type and combination of environmental protection systems associated with the landfill. Since landfill traditions vary significantly among different countries (and some times also within different regions of countries) characteristic landfill profiles representing the importance of various landfill types are required for estimation of emissions from the disposal stage of an international production system. **Table 3** shows the relative importance of landfill types L1 to L4 in the Netherlands, Germany and Denmark and the importance of landfill gas combustion in the three countries, based on the tonnage of waste disposed. Germany is divided into two regions Germany (E) and Germany (W) because waste is treated differently in the two regions of the country due to different traditions in the former East- and West Germany. The results of the survey of waste management in The Netherlands, Germany and Denmark have been entered to LCA-LAND as default values for the present waste management technology in the three countries. The total fraction (SUM(L1...L4)) represent the fraction of waste disposed at landfills in each country. The remaining fraction of municipal solid waste is treated by incineration and eventually composting, crushing etc. A parallel computer tool (LCA-INC) for estimation of product specific emissions from municipal solid waste incineration will be presented by ERICHSEN and HAUSCHILD (1998).

Table 3: National landfill profiles for The Netherlands, Germany and Denmark plus specific landfill profile for the fictive waste product distributed in the three countries

Landfill type [1]	The Netherlands[2]	Germany (E)[3]	Germany (W)[4]	Denmark[5]	Fictive waste product
L1 (with leachate treatment)	0.35	0.0	0.0	0.14	0.15
L2 (with water stopping top cover)	0.0	0.9	0.1	0.0	0.29
L3 (with leach. treatm. and water stop. top cover)	0.15	0.1	0.6	0.0	0.21
L4 (no leach. treatm. or water stop. top cover)	0.0	0.0	0.0	0.015	0.00
SUM(L1..L4)	0.5	1.0	0.7	0.15	0.65
LGC[6]	0.2	0.05	0.34	0.0	0.16

1) Landfill types are described in more details by NIELSEN and HAUSCHILD (1998)

2) 50% of the municipal solid waste was landfilled in The Netherlands in 1994. Waste disposed at landfills with unknown top-cover is assumed to be disposed at landfills "without water stopping top cover". AOO; Va&RIVM (1995) and AOO 1995

3) 100% of the municipal solid waste was landfilled in East Germany in 1993. Values in the table relate to the number of landfills because no information was available about the amounts of waste disposed at various types of landfills (Umweltbundesamt, 1994)

4) 70% of the municipal solid waste was landfilled in West Germany in 1993 (THOMÉ-KOZMIENSKY, 1994; Statistisches Bundesamt, 1996). Values relate to the total landfill volume in West Germany and were calculated on the basis of data given in Umweltbundesamt, 1994)

5) 15% of the municipal solid waste was landfilled in Denmark in 1995 (MILJOSTYRELSEN, 1996). 90% of the disposed waste was disposed at landfills equipped with leachate collection. Water stopping top cover is not used in Denmark (RENDAN, 1997)

6) LGC: Landfill gas combustion

The "fictive waste product"-column represents the overall importance of each landfill type and of landfill gas combustion for the fictive waste product discussed in **section 3.**

3 Estimation of Emissions from a Fictive Waste Product

In order to illustrate inputs and outputs from the LCA-LAND computer tool, an example based on a fictive waste product composed of five representative components (→ *Table 4*) is presented in this section. The waste product could in principle originate from any step in the life cycle of the product, but in order to illustrate simultaneous estimation of emissions in more than one country, we assume that the waste product is the product it self in the disposal phase.

A qualitative overview of the most important substance transportation routes in landfills is presented in **section 3.1** and LCA-LAND input and output data are provided in **section 3.2** respectively **3.3.** The purpose of the qualitative overview of substance transportation routes in **section 3.1** is twofold. Firstly to present the background information required for the accomplished estimations and secondly to serve as a reference for expected emission levels during verification of the computer tool in **section 4.**

3.1 Substance transportation routes

The focus of this section is only on the transportation routes relevant for the fictive waste product. NIELSEN and HAUSCHILD (1998) should be consulted for a general description of the transportation routes used in the computer tool.

3.1.1 In the landfill

A fraction of toluene may remain in the landfill throughout the simulated period of 100 years, while other fractions may dissolve in the leachate, evaporate into the atmosphere and/or become degraded biologically (KJELDSEN and CHRISTENSEN, 1997). Cellulose is converted to methane (CH_4), and CO_2 (HAM and BARLAZ, 1989) and dissolved organic matter in the leachate (BELEVI and BACCINI, 1989). The main fraction of methane is evaporating into the atmosphere, but also a small amount is dissolved and emitted with the leachate (BELEVI and BACCINI, 1989). PVC is recalcitrant in the landfill (MØLLER et al., 1996) and remains intact in the landfill throughout the 100-year period. Copper is slowly dissolved in the leachate and a very small fraction is leaving the landfill within the 100-year period (FINNVEDEN, 1996). The main parts of copper remains in the landfill throughout the 100-year period. Chloride is highly soluble in water, and all chloride is leaching out of the landfill within the 100-year period (BELEVI and BACCINI, 1989).

3.1.2 In the leachate treatment plant

The fraction of toluene and methane (from degradation of cellulose) which enters leachate treatment plants may partly become biologically degraded and partly evaporate into the atmosphere (JACOBSEN et al., 1996). Only a minor fraction of methane and toluene may pass through the leachate treatment plant to aquatic recipients or become sorbed to sludge and discharged to soil. Dissolved organic matter from cellulose is aerobically biodegradable and is almost completely mineralized in the leachate treatment plant. The main fraction of copper is sorbed to sludge and disposed in the soil

environment, while a smaller fraction of the copper remains dissolved in the water and is discharged into aquatic recipients (LESTER, 1983). Chloride is not susceptible to biological degradation or sorption to sludge and all chloride passes through the leachate treatment plant to aquatic recipients.

3.1.3 In the landfill gas combustion plant

The fractions of methane and toluene which enter landfill gas combustion plants is completely mineralized to CO_2 and water. Energy produced during methane and toluene combustion is utilized for heat and/or electricity production (STEGMANN, 1996).

3.2 Input data for the quantitative estimation of emissions in LCA-LAND

The estimation of emissions from waste products disposed in the landfills is based on following input data:

1) Masses of waste product components.
2) International distribution of the product.
3) Physical/chemical and biological constants (only SOCs).
4) Distribution coefficients (e.g. between water, atmosphere and sludge after leachate treatment)
5) Conversion factors (e.g. g CO_2 pr. g degraded cellulose).

Each group of input data is discussed with respect to the fictive waste product in the following.

3.2.1 Masses of waste product components

Masses and names of components as listed in **Table 4** are used directly as input to LCA-LAND.

Table 4: Composition of the fictive waste product

Component	Weight [g]	Group[1]
Toluene	5	SOCs[2]
Cellulose	40	GOM[3]
Polyvinyl chloride (PVC)	20	Inert components
Copper	10	Metals
Chloride	25	Inorg. non-metal

[1] The grouping of components is described in NIELSEN and HAUSCHILD (1998)
[2] SOC: specific organic compounds
[3] GOM: general organic matter

3.2.2 International distribution of the product.

Table 3 shows that the landfill technology varies significantly among the four investigated countries/regions, and information about the international distribution of the product is required for correct estimation of emissions. **Table 5** shows the international sale of the product, which is disposed as the fictive waste product after usage. It is assumed that only a negligible fraction of the product is passing the border after sale and hence, that the product is treated as waste in the countries according to the fractions of the sale. The lifetime of the product is short (a few years) and the product is assumed to be treated by the present landfill technology (1995) in each country.

The fractions of the fictive waste product disposed in various types of landfills (L1 to L4) and the fractions of the product disposed at landfills equipped with landfill gas combustion are calculated in LCA-LAND, taking national landfill profiles in **Table 3** and the distribution scenario in **Table 5** into account. The results are shown in the "fictive waste product" column in **Table 3**.

Table 5: International sale of the product which is disposed after use as the fictive waste product

Country	%
The Netherlands	40
Germany (E)[1]	30
Germany (W)[2]	20
Denmark	10

[1] former East Germany
[2] former West Germany

3.2.3 Physical/chemical and biological constants

The physical/chemical and biological data listed in **Table 6** are used for estimation of distribution coefficients between emissions (atmosphere, water and soil), degradation and remains in the landfill for the disposed toluene. As discussed by NIELSEN and HAUSCHILD (1998), physical/chemical parameters have general validity while the degradation rate may vary from landfill to landfill as well as within each landfill. Although a fraction of toluene may be degraded aerobically in the landfill top-cover (KJELDSEN et al., 1996) and furthermore some toluene may be degraded under reduced redox conditions (CHRISTENSEN et al., 1994) the significance of the degradation is unknown. Until more information is available about degradation in landfill top covers and in landfills, we find the conservative assumption, that no toluene is degraded ($\lambda_{toluene}$ = 0 year^{-1}) most appropriate.

Table 6: Physical/chemical and biological constants for tuluene

Phys./chem. parameter	Unit	Toluene
Molar weight	g mol^{-1}	92 [1]
Vapor pressure	Pa	3800 [1]
Henry's law coefficient K_H	-	0.28 [1]
Octanol-water partition coefficient, Log K_{ow}	-	2.69 [1]
First order degradation rate constant, λ	Year^{-1}	0
Heat of combustion	kJ g^{-1}	42.5 [2]

[1] MACKAY et al. (1992)
[2] CRC (1984)

3.2.4 Distribution coefficients

The distribution of waste product components between emissions (atmosphere, water and soil), degradation and remains in the landfill are partly based on estimated coefficients, partly based on standard coefficients in LCA-LAND, and partly based on input data characterizing the actual components. Table 7 summarizes all the required input data for all components of the fictive waste product, and also indicates which parameters are estimated in LCA-LAND and which parameters are fixed standard coefficients. Estimation of distribution coefficients and determination of standard coefficients used in LCA-LAND is discussed in Nielsen and Hauschild (1998). All data concerning methane (degradation product of cellulose) are standard in LCA-LAND.

Copper distribution coefficients in landfills are based on the "best available emission factors" deduced by FINNVEDEN (1996) from measured metal concentrations in leachate. Toluene is highly flammable (Hazardous Substance Data Bank, 1995), and 100% is assumed to be combusted completely in the landfill gas combustion plant.

The distribution of toluene and cellulose in the leachate treatment plant are estimated by model simulations in Simpletreat 3.0 (STRUIJS et al., 1991; MIKKELSEN et al., 1996) assuming that the leachate treatment plants are equivalent with European standard activated sludge waste water treatment plant with respect to the fate of pollutants (NIELSEN and HAUSCHILD, 1998).

The distribution coefficients of copper in leachate treatment plants are based on average removal efficiency of copper in 14 activated sludge treatment plants, pilot plants and laboratory scale plants (LESTER, 1983) assuming that copper removed during the treatment process is sorbed to the sludge and distributed on farming land (soil).

3.2.5 Conversion factors

Toluene and cellulose are subject to conversion processes in the landfill and the associated environmental protection units. In order to estimate the masses of conversion products produced during degradation and combustion processes, conversion factors between mother products and conversion products are required. Stoichiometric conversion factors for toluene and cellulose in the landfill, the landfill gas combustion plant and the leachate treatment plant are listed in Table 8.

Calculations of methane and CO_2 formation from cellulose in landfills are based on a generalized formula valid for anaerobic decomposition of general organic matter under methanogenic redox conditions (FINNVEDEN et al., 1995). CO_2 originating from fossil sources (toluene) contribute to the global warming, while CO_2 originating from biological sources of more recent origin (cellulose) does not (HAUSCHILD and WENZEL, 1997). This difference is taken into account in the final inventory in section 3.3. Emission of water from the landfills is neglected in the inventory and is also disregarded in Table 8.

Table 7: Distribution coefficients of waste product components in landfills, landfill gas combustion plants and leachate treatment plants

	Toluene	Cellulose[a]	PVC[a]	Copper	Chloride[a]
Landfills					
fraction in leachate	0.12[b,c] or 0.43[b,d]	0.01[c] or 0.001[d]	0	0.00007[h]	1
fraction in landfill gas	0.60[b,c] or 0.55[b,d]	0.99[c] or 0.999[d]	0	0[h]	0
fraction remaining in waste	0.29[b,c] or 0.01[b,d]	0	1	0.99993[h]	0
fraction degraded	0	0.99[c] or 0.999[d]	0	-[e]	0
Landfill gas combustion plants					
fraction combusted	1[f]	1[g]	-	-	-
Leachate treatment plants					
fraction emitted to the atmosphere	0.10[f]	0	-	0[i]	0
fraction emitted to water	0.13[f]	0	-	0.34[i]	1
fraction emitted to soil	0.022[f]	0	-	0.66[i]	0
fraction degraded	0.75[f]	1[f]	-	-	0

[a] All cellulose, PVC and chloride distribution coefficients are standard in LCA-LAND
[b] estimated in LCA-LAND (NIELSEN and HAUSCHILD, 1998) based on input data listed in table 6
[c] Landfills without water stopping top cover
[d] Landfills quipped with water stopping top cover
[e] -: Not relevant
[f] Estimated in Simpletreat (STRUIJS et al., 1991; MIKKELSEN et al., 1996)
[g] Hazardous Substance data Bank (1995)
[h] FINNVEDEN (1996)
[i] LESTER (1983)

Table 8: Stoichiometric conversion factors for degraded/combusted components

	Toluene[a]	Cellulose[b]
Landfill	-	0.30 g CH_4 g^{-1} 0.81 g CO_2 g^{-1}
Leachate treat. plant	3.35 g CO_2 g^{-1}	1.63 g CO_2 g^{-1}
Combustion plant	3.35 g CO_2 g^{-1}	-

[a] fossil origin
[b] biological origin

3.3 Output data of LCA-LAND – the inventory

Based on the previously described input data and standard coefficients in the model, emissions from the fictive waste product are estimated in LCA-LAND. The inventory of emissions for each component as well as the sum of emissions representing the entire product is presented in Table 9.

4 Verification of LCA-LAND

In order to verify the LCA-LAND inventory of the fictive waste product the output should have been compared with measured emissions from true landfills. However, this comparison is not possible since (i) waste products are distributed at several landfills, (ii) the emissions from the studied waste product are mixed with emissions from other substances present in the landfills (iii) the emissions are realized during the coming 100 years. Hence, the verification of the tool is based on mass balance calculations and sensitivity analysis as the best alternative.

4.1 Mass balance

The purpose of the mass balance is to verify correctness of the calculations in LCA-LAND and mass balances have been made for all components of the fictive waste product plus a number of additional test substances (e.g. dichlorobenzene,

Table 9: Inventory of emissions (g) and energy production (kJ) from the fictive waste product disposed as municipal solid waste in the Netherlands, Germany and Denmark

	Toluene	Cellulose	PVC	Copper	Chloride	Total
Emissions to atmosphere during 100 years						
Toluene	1.7					1.7
Methane		7.1				7.1
CO_2 fossil	0.72					0.72
CO_2 biogen		23				23
Emissions to water during 100 years						
Toluene	0.054					0.054
Methane		$3.8 \cdot 10^{-4}$				$3.8 \cdot 10^{-4}$
Cellulose		$2.6 \cdot 10^{-2}$				$2.6 \cdot 10^{-2}$
Copper				$7.9 \cdot 10^{-5}$		$7.9 \cdot 10^{-5}$
Chloride					16	16
Remains in the underground after 100 years						
Toluene	1.3					1.3
Methane		~ 0				0
PVC			13			13
Copper				6.6		6.6
Emissions to soil during 100 years						
Toluene	$1.9 \cdot 10^{-3}$					$1.9 \cdot 10^{-3}$
Methane		$1.3 \cdot 10^{-6}$				$1.3 \cdot 10^{-6}$
Copper				$6.5 \cdot 10^{-5}$		$6.5 \cdot 10^{-5}$
Energy production during 100 years						
The Netherlands	2.7	15				18
East Germany	0.50	2.8				3.3
West Germany	2,3	13				15
Denmark	0	0				0
Energy, total	5.4	30				35

fat, polyethylene, cadmium, and sulfur). The results for toluene are presented in Table 10 as an example. Based on input masses of toluene (C_7H_8) disposed in the landfills and emissions of toluene, CO_2 and H_2O to various recipients, total masses of input and output carbon (C) and hydrogen (H) have been calculated.

Table 10 shows that input and output masses of carbon and hydrogen are equal and hence that no mass build up or mass loss has occurred during calculations in the model. All conducted mass balances are based on exact input data and show complete agreement with output of the individual substances.

from various types of components in various types of landfill are estimated, and the results are compared with each other as well as with expected levels of emissions based on the literature (→ *section 3.1*).

Sensitivity analyses have been made for the fictive waste product (1 g of each component) disposed in each landfill type. The results for toluene, cellulose and copper are presented here as examples. The fates of chloride and PVC are not discussed any further, because emissions/ remains in the landfill (as expected) were independent of the landfill type as well as the presence of environmental protection units.

Table 10: Mass balance for toluene (C_7H_8) disposed landfills

	Mass [g]	MW [g mol^{-1}]	C [g]	H [g]
Input				
Toluene	3.27750000000[a]	92	2.99250000000	0.28500000000
Output				
Toluene	3.06332863475[b]	92	2.79695223173	0.26637640302
CO_2	0.71700848366	44	0.19554776827	0
H_2O	0.16761237280	18	0	0.01862359698
Sum of output			2.99250000000	0.28500000000

[a] The total mass of disposed toluene multiplied by the total fraction of the product disposed in landfills (SUM(L1..L4) → *Table 3*)
[b] Sum of emissions to atmosphere and water

4.2 Sensitivity analysis

The purpose of the sensitivity analysis is twofold. Firstly to assess how the composition of emission from various components change as landfill conditions change, secondly to evaluate the performed division of landfills in types L1 to L4 with/without landfill gas combustion. The emissions

Figure 4 shows the estimated emissions/remains of toluene in the eight possible different combinations of landfills (the properties of landfill types L1 to L4 are illustrated in NIELSEN and HAUSCHILD (1998), → *Figure 2*).

The atmospheric emissions of toluene are at the same level for all landfill types without landfill gas combustion units,

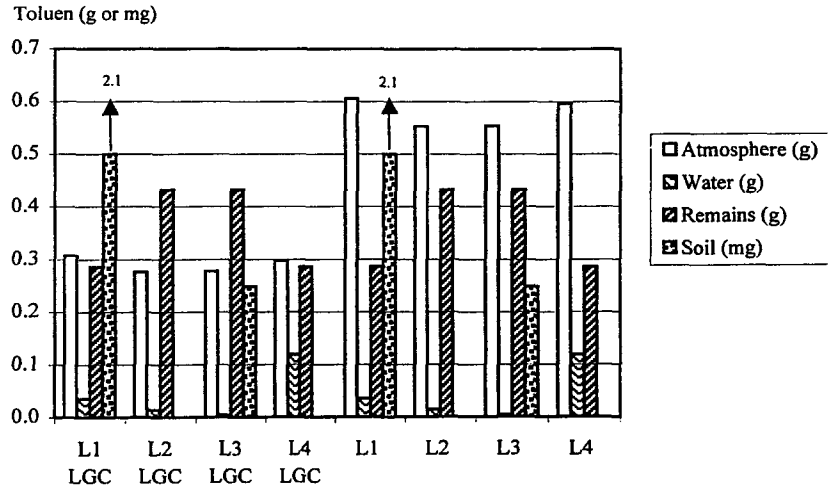

Fig. 4: Estimated emissions of toluene to atmosphere, water and soil during 100 years plus remains in the landfill after 100 years. Landfill types L1 to L4: → *Table 3*. LGC: landfills equipped with landfills gas combustion units

and the atmospheric emissions are reduced by a factor 2 in the presence of landfill gas combustion units (LGC). Generally, atmospheric emissions are slightly reduced at landfills equipped with water-stopping top-cover (compare L2 and L3 with L4) and slightly increased at landfills equipped with leachate treatment units (compare L4 and L1). The slight increase of atmospheric emissions at landfills equipped with leachate treatment can be explained by evaporation of toluene (which is very volatile, → *Table 6*) during aeration of the water in the leachate treatment plant, while the slight decrease of atmospheric emissions at landfills equipped with water-stopping top-cover can be explained by reduced diffusion to the atmosphere.

Emission of toluene to aquatic recipients is independent of the presence of landfill gas combustion units, but is reduced at landfills equipped with leachate treatment units (compare L4 with L1) and water-stopping top-cover (compare L4 with L2). The lowest emissions of toluene to aquatic recipients are observed at landfills equipped with both leachate treatment and water-stopping top-cover (compare L1 and L2 with L3). Emissions to water are reduced by a factor of 27 at landfills equipped with both top-cover and leachate treatment (compare L3 with L4). At landfills equipped with leachate treatment facilities a considerable fraction of the toluene is degraded or evaporates into the atmosphere as discussed above. At landfills equipped with water-stopping top-cover only a small fraction of the precipitation is entering the landfills resulting in a significant decrease in leachate generation and hence water transportation of pollutants. This explains the effect of water-stopping top-cover on aquatic emissions of toluene.

Remains of toluene are significantly higher at landfills equipped with water-stopping top-cover than at landfills without (compare L2 and L3 with L1 and L4). The high level of toluene remains at landfills equipped with water-stopping top-cover is explained by the reduced evaporation and water transportation of toluene at these landfills, as discussed above.

Due to sorption of toluene to the sludge in the leachate treatment plants, a small amount of toluene is emitted to soil at landfill types L1 and L3 as all sludge is assumed to be disposed on farm land (note that emissions to soil in **Figure 4** are given in mg). The significantly lower level of emissions of toluene to soil at landfills equipped with water-stopping top-cover (L3) compared with landfills without water-stopping top-cover (L1) can also be explained by the low leachate generation at these landfills as discussed above.

Emissions of fossil CO_2 from disposed toluene only occur at landfills equipped leachate treatment and landfill gas combustion facilities (data not shown). This is due to the assumption that no toluene is degraded in the landfill and the fact that a significant amount of toluene is degraded respectively combusted in the leachate treatment and landfill gas combustion units.

Similar analyses have been conducted for methane (from degradation of cellulose, data not shown). Although remains of methane and emissions of methane to water were at a much lower level than for toluene (→ *Figure 4*) the general emission pattern was similar and in very good agreement with the differences in physical/chemical properties of the two compounds.

Cellulose is only emitted to aquatic recipients and the emission pattern is independent of the presence of landfill gas combustion plants (→ *Figure 5*). Cellulose has the same emission pattern as aquatic emissions of toluene and methane, although cellulose emissions are reduced by a factor 50 at landfills equipped with leachate treatment and water-stopping top-cover (compare L3 and L4). It is difficult to compare the cellulose results (based on a simple model) with toluene results (based on the more complex SOC-model and Simpletreat-model), but it is interesting to note that the results for toluene and cellulose generally are in agreement and that the significance of environmental protection units, as expected are at the same level.

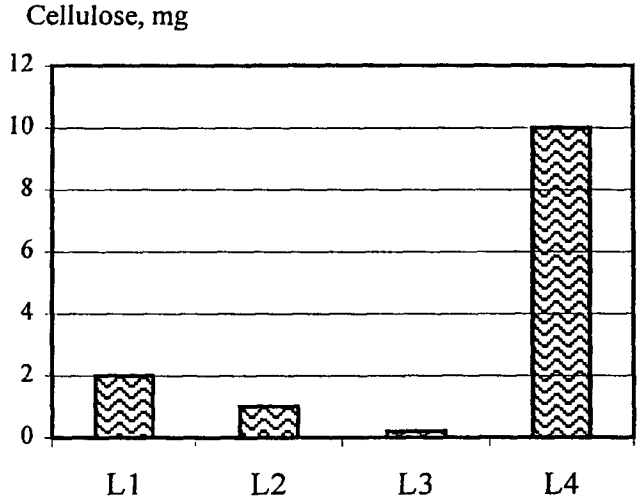

Fig. 5: Estimated emissions of cellulose to water from landfills during 100 years

Remains of copper in the landfills and emissions of copper to water and soil are illustrated in **Figure 6**. Landfill gas combustion units are ignored in the figure since no copper is emitted to the atmosphere. **Figure 6** shows that emissions of copper to water and soil are very small compared to the amounts of copper remaining in the landfills after 100 years. The emission of copper to water is significantly reduced at landfills equipped with water-stopping top-cover (compare L2 with L4), as well as at landfills equipped with leachate treatment facilities (compare L1 with L4). However, the reductions of copper emissions to aquatic recipients results in increased soil emissions at landfills equipped with leachate treatment (see L1 and L3) and increased remains of copper at landfills equipped with water-stopping top-cover (L2 and L3) and none of the environmental protection units really

solve the potential problem of copper emissions. Since the modeling of the fate of metals in the landfill system is partly based on measured emissions and partly based on pragmatic assumptions (NIELSEN and HAUSCHILD, 1998) it is difficult to compare the exact levels of copper emissions. However, it is important to note that although the estimated emissions may be uncertain and incomparable at the present level, it is clear that emissions to water and soil are extremely small and that almost all copper remains in the landfill after the 100-year period in any case.

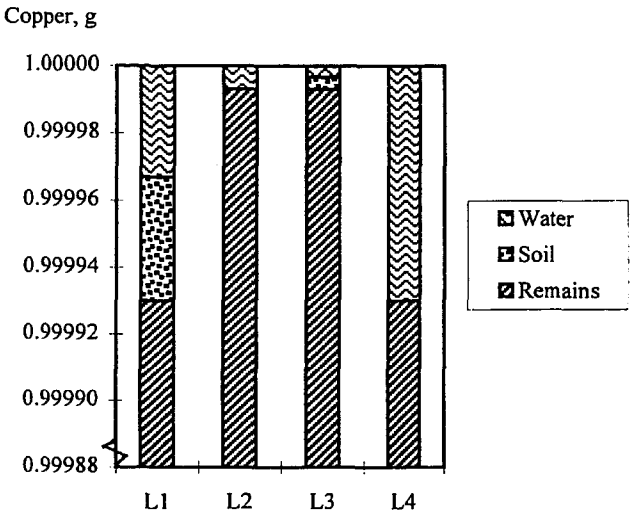

Fig. 6: Estimated emissions of copper to water and soil during 100 years plus remains in the landfill after 100 years

5 Discussion

Based on a comprehensive framework of assumptions and approximations about landfills (NIELSEN and HAUSCHILD, 1998) the computer tool LCA-LAND for estimation of emissions from waste products disposed as municipal solid waste in landfills has been presented and verified in this paper.

Since it was not possible to compare the estimated emissions with measured emissions from the landfills, the tests of LCA-LAND have been limited to mass balances and sensitivity analyses. The mass balances show that no mass is gained or lost during the calculations and a good agreement between the obtained results and expected results (based on properties of components and landfill types) appeared in the sensitivity analysis. In this section some remaining aspects concerning the quality, usefulness and further development of the landfill model (NIELSEN and HAUSCHILD, 1998) and the computer tool will be discussed.

Some would argue that the division of landfill types into four different categories (with and without landfill gas combustion) is too simple and that a more sophisticated modeling concept would allow for more accurate calculations, while others would argue that the modeling concept is too complicated and that all landfills should be pooled in one group and modeled uniformly. Based on the results of the sensitivity analysis, we find that the presented modeling concept is a reasonable compromise between the two viewpoints. More sophisticated models would demand information which is hardly available and the estimated emissions would supposedly be within the same order of magnitude as those estimated in the present model. Simpler models (e.g. based on one average landfill type) would be easier to deal with than the model presented here, but the uncertainty of the results would increase significantly.

Although the uncertainty of modeling of emissions from the landfills and associated environmental protection units was assessed by NIELSEN and HAUSCHILD (1998), no attempts have been made to quantify the uncertainty of emissions estimated in LCA-LAND. In the future, LCA-LAND should be extended to include estimation of uncertainty using, e.g. the Monte Carlo method (WENZEL et al., 1997)

Many modeling assumptions and approximations behind the computer tool presented in this paper are quite simple and as already discussed by NIELSEN and HAUSCHILD (1998) there is an obvious need for more scientifically based model parameters to provide more accurate estimations of emissions. However, we find that the best estimates of emissions from waste products disposed at landfills are much more qualified and useful in LCA than just neglecting the emissions, which is absolutely wrong and misleading. To improve future estimation of emissions from waste products disposed at landfills, we find that the main task is to acquire more knowledge of landfill processes at a general level as well as at a waste product oriented level and hereby quantify key parameters in the model at a higher scientific level.

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Product Specific Emissions from Municipal Solid Waste Landfills
Part I: Landfill Model (Int. J. LCA 3 (3) 1998)

Per H. Nielsen, Michael Hauschild

For the inventory analysis of environmental impacts associated with products in Life Cycle Assessment (LCA) there is a great need for estimates of emmissions from waste products disposed at municipal solid waste landfills (product specific emissions). Since product specific emissions can not be calculated or measured directly at the landfills, they must be estimated by modeling of landfill processes. This paper presents a landfill model based on a large number of assumptions and approximations concerning landfill properties, waste product properties and characteristics of various kinds of environmental protection systems (e.g. landfill gas combustion units and leachate treatment units). The model is useful for estimation of emissions from waste products disposed in landfills and it has been made operational in the computer tool LCA-LAND presented in a following paper. In the model, waste products are subdivided into five groups of components: general organic matter (e.g. paper), specific organic compounds (e.g. organic solvents), inert components (e.g. PVC), metals (e.g. cadmium), and inorganic non-metals (e.g. chlorine), which are considered individually. The assumption and approximation used in the model are to the extent possible scientifically based, but where scientific information has been missing, qualified estimates have been made to fulfill the aim of a complete tool for estimation of emmissions. Due to several rough simplifications and missing links in our present understanding of landfills, the uncertainty associated with the model is relatively high.